

Top Mass at the Tevatron

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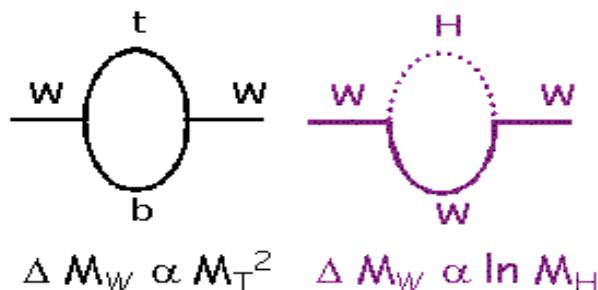
On behalf of the D0 and CDF Collaborations

HCP 2006 at Duke, May 22-26, 2006

Why do we care about Top Mass?

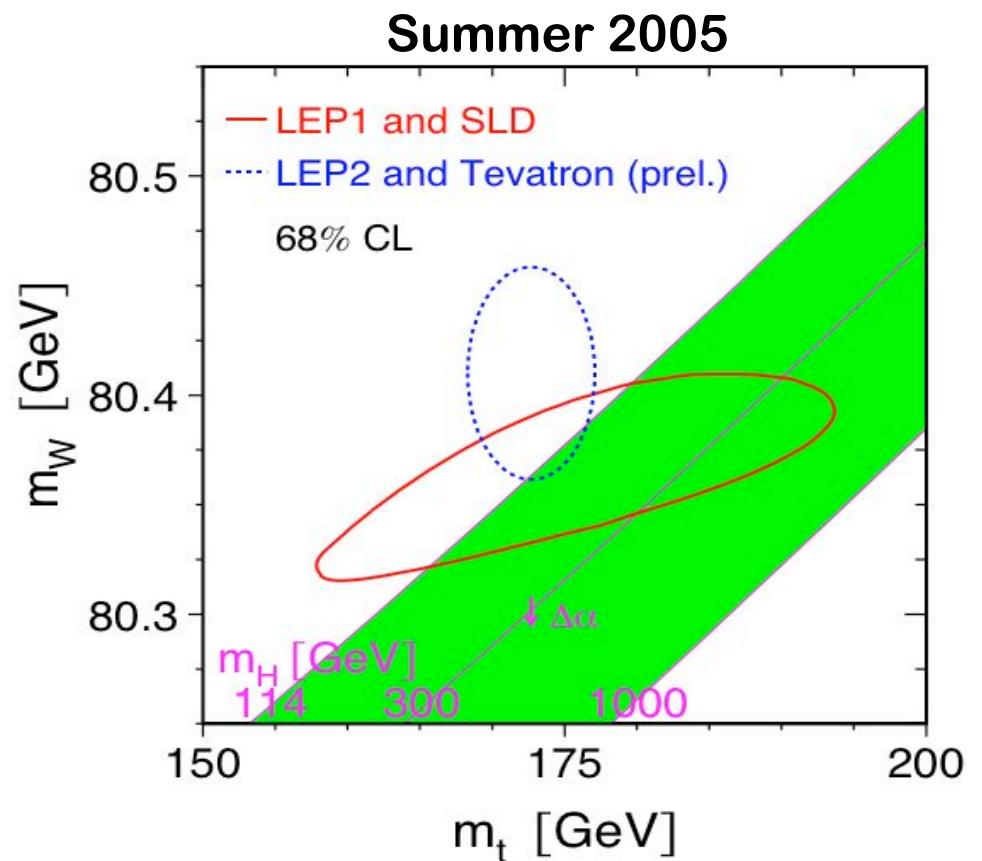
- Top mass is a fundamental SM parameter

- important in radiative corrections:



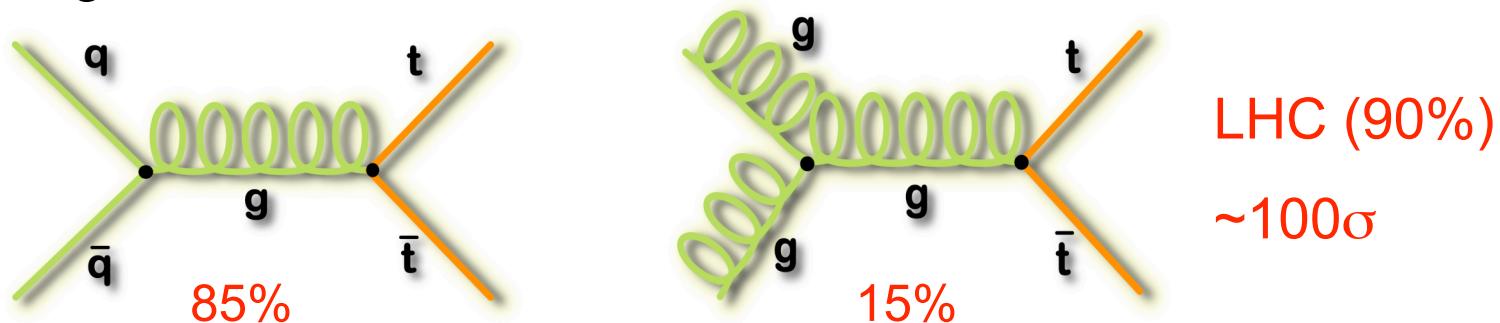
- Yukawa coupling ~ 1
- Consistency check of SM, and it constrains M_{Higgs} with M_w and other electroweak precision measurements

- A key to understand electroweak symmetry breaking?
- Constraint on SUSY models



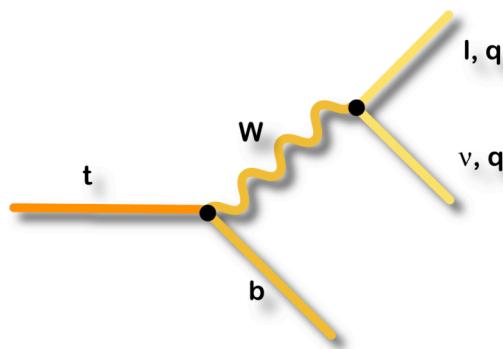
Top Production and Decay

- At the Tevatron, mainly primarily produced in pairs ($\sigma \sim 7\text{ pb}$) via strong interaction.

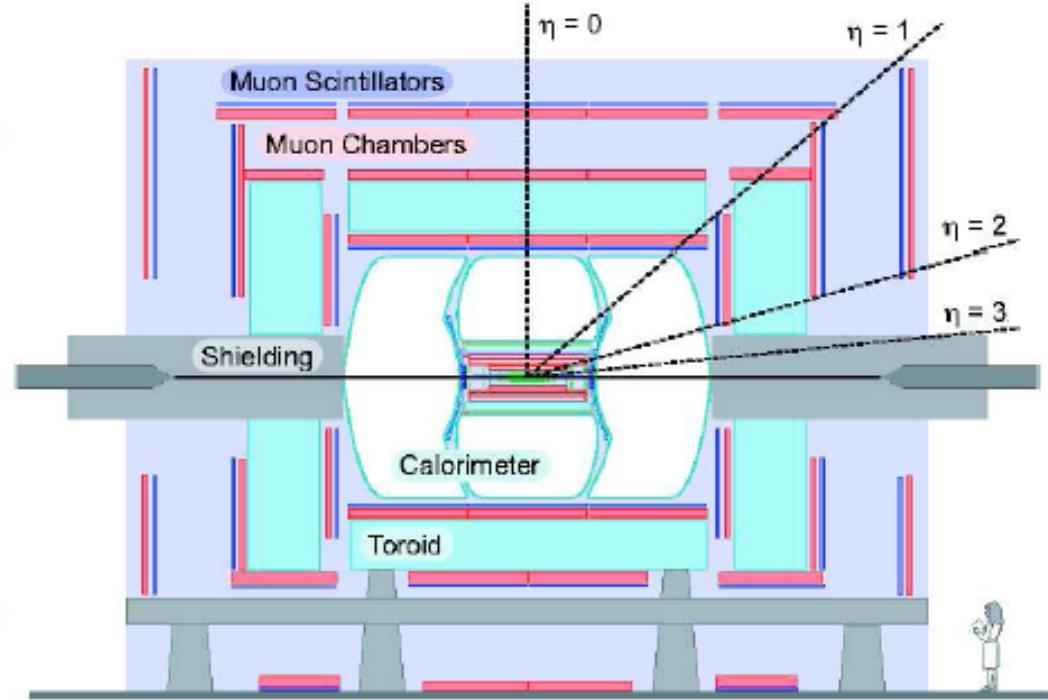
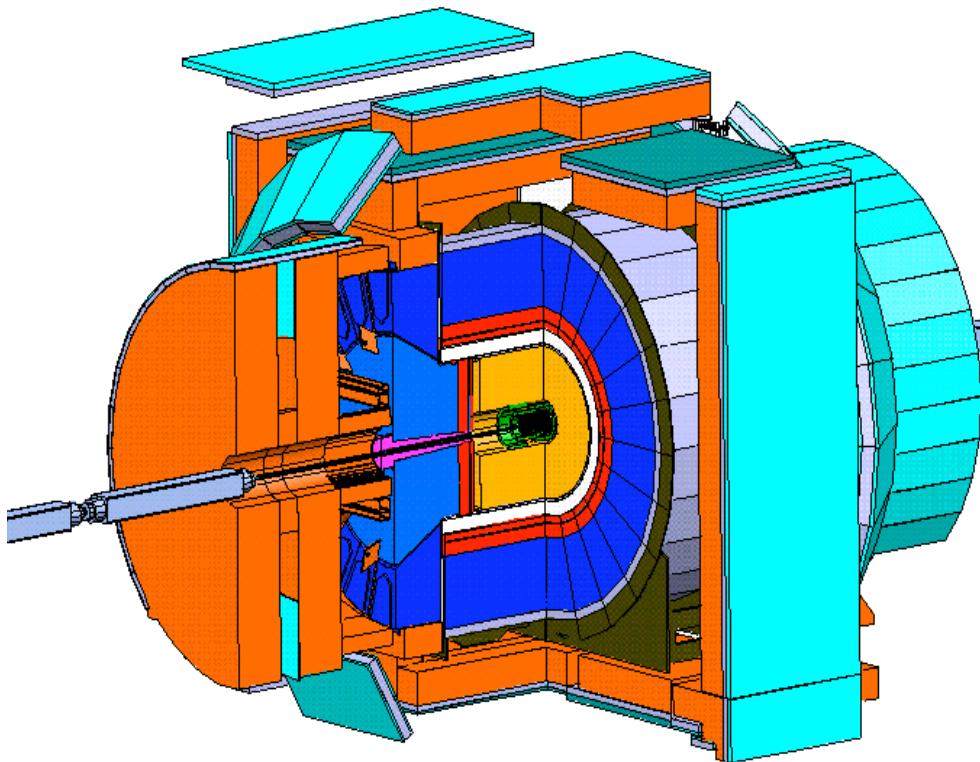


- Top decays as free quark due to large mass ($\tau_{\text{top}} \sim 4 \times 10^{-25} \text{ s}$)

- Dilepton (5%, small bkgds)
2 leptons (e/μ), 2 b jets, missing E_T (2νs)
- Lepton+Jet (30%, manageable bkgds)
1 lepton (e/μ), 4 jets (2 b jets), missing E_T (1ν)
- All-hadronic (44%, large bkgds)
6 jets (2 b jets)



The CDF and DØ Detectors

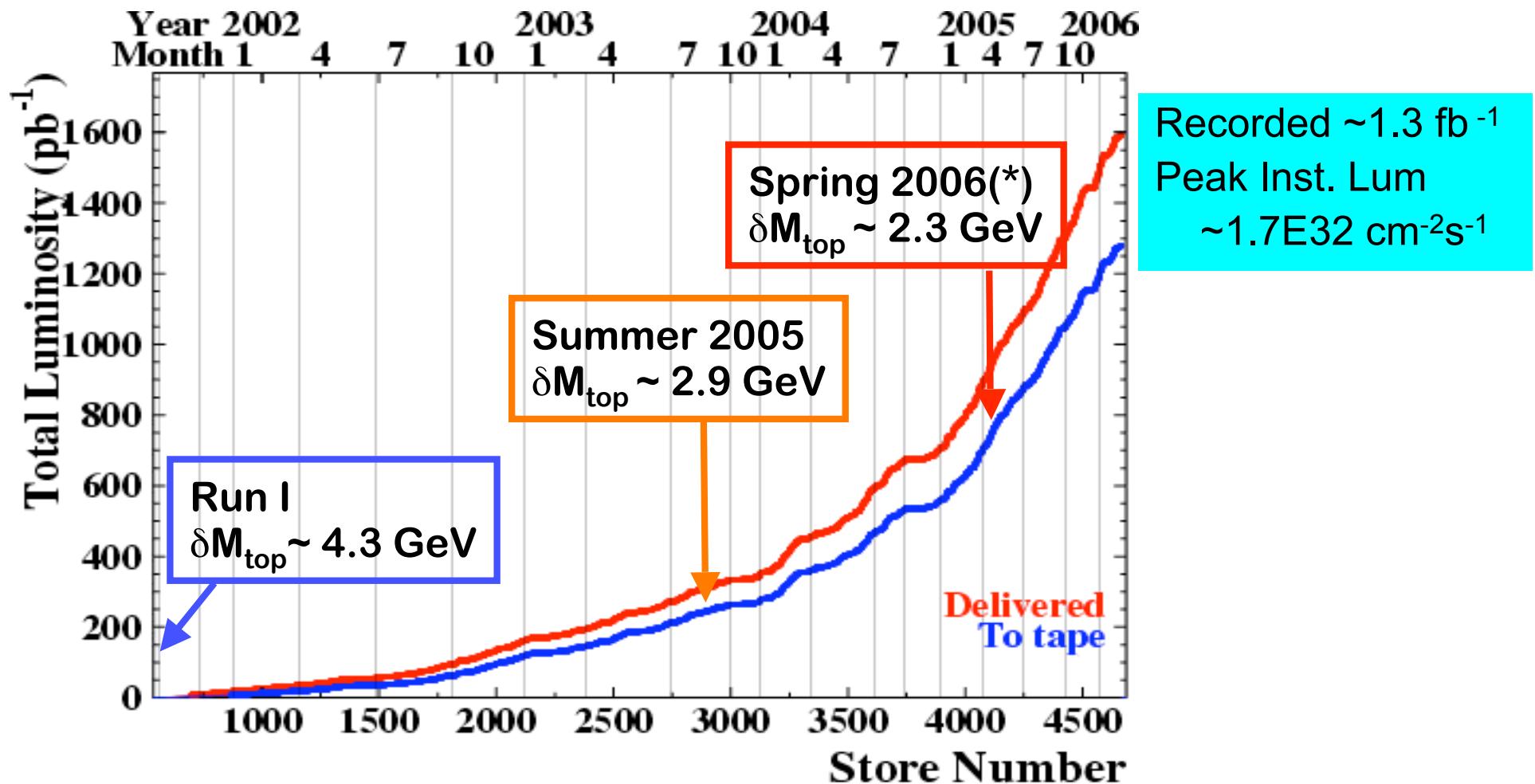


- Calorimeters ($\sigma/E \sim 80\% / \sqrt{E}$)
- Precision tracking with Si:
- Muon chambers
- Excellent muon coverage(D0), excellent tracking (CDF)



Multi-purpose detector;
precision measurements
search for new physics

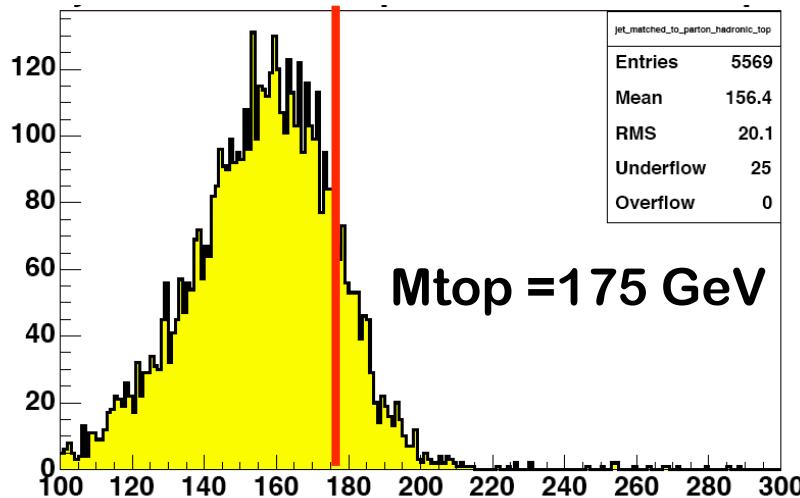
Great Performance (Tevatron, D0, and CDF)



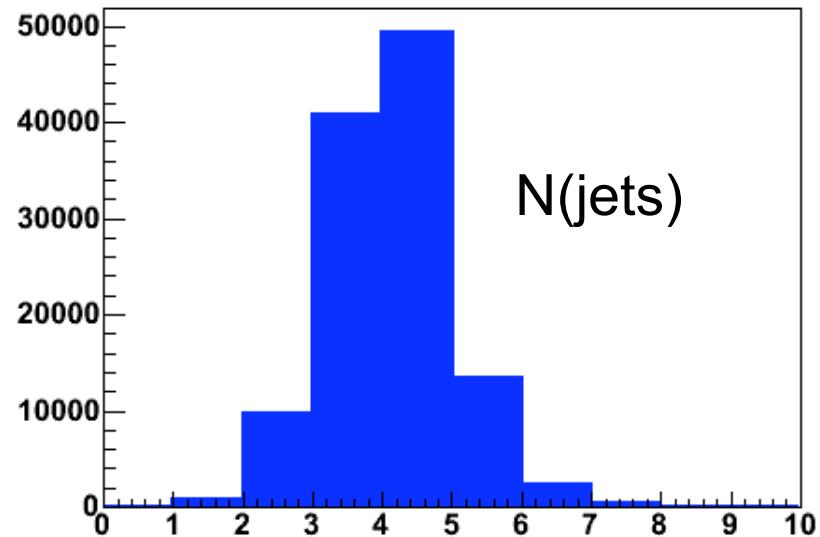
* Not all D0 data included

M_{top} Measurement : Challenge 1

- Not a just calculation of the invariant mass of $W(jj)$ and $b!!!$



Why $M(bjj) \neq 175 \text{ GeV?}$



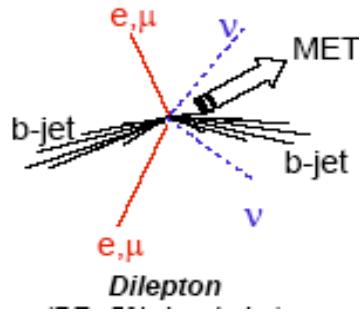
- Measured jet energy
 \neq quark energy from top decay
 - Quarks: showering,
hadronization, jet clustering
 - Extra radiated jets

- Excellent jet energy correction
and good modeling of extra
gluon radiations (40%)

Challenge 2

- There are two top quarks, not all final states available
 - Good to have more than one: but too many possibilities to find a correct combination (all jets: 90), not enough information for dilepton channel

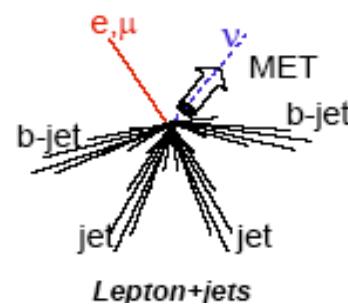
3 constraints: two $M(w)=80.4$, one $M(t)=M(tb)$



Ncomb(bttag) 2(2)

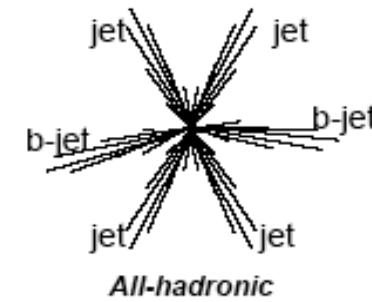
2 missing ν

Unconstrained:
Small BR



12 (6)

1 missing ν
Overconstrained:
Golden Channel



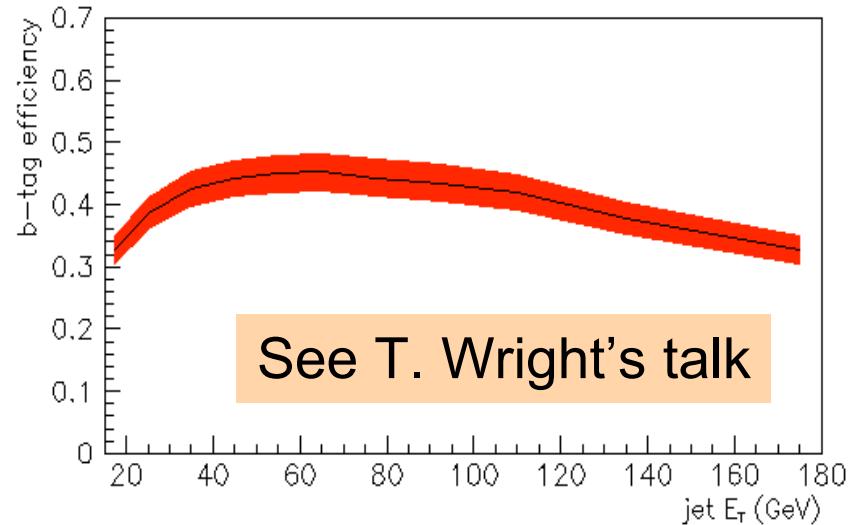
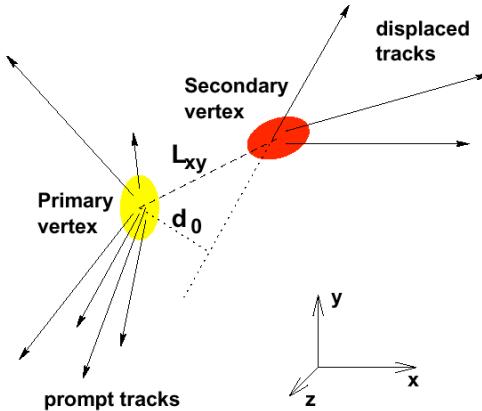
360(90)

No missing
Overconstrained:
Large bkgds

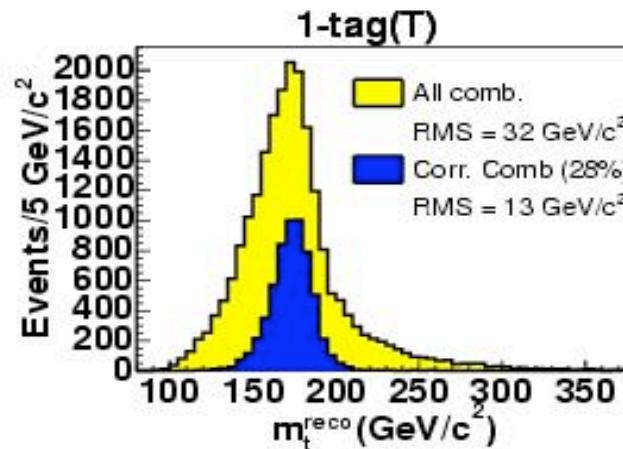
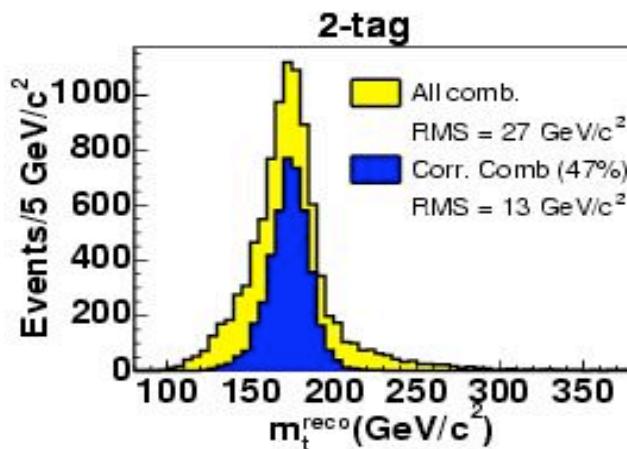
- B-tagging help!

B-tagging

- B-tag: SecVtx tagger



- B-tagging helps: reduced wrong comb., and improves resolution.



Top Mass Measurements

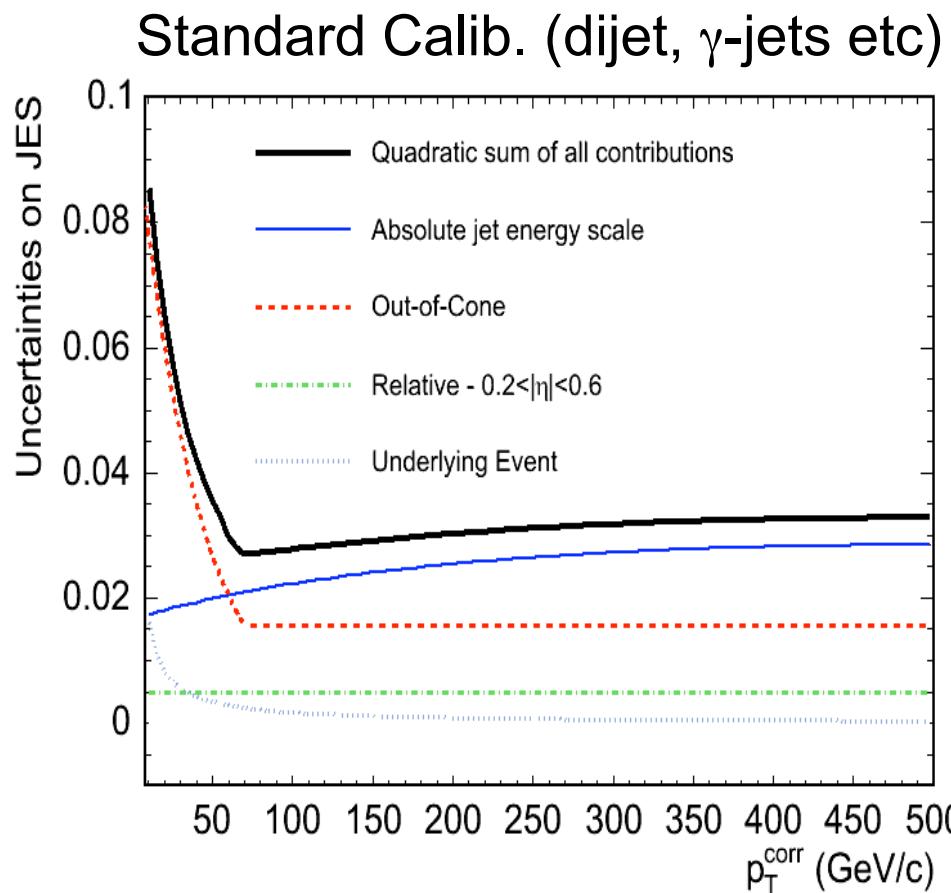
Template

- Reconstruct m_t event-by-event - the best value per each event
- Create “templates” using simulated events with different top mass values, and backgrounds.
- Maximum Likelihood fit using signal+backgrounds templates

Matrix Element

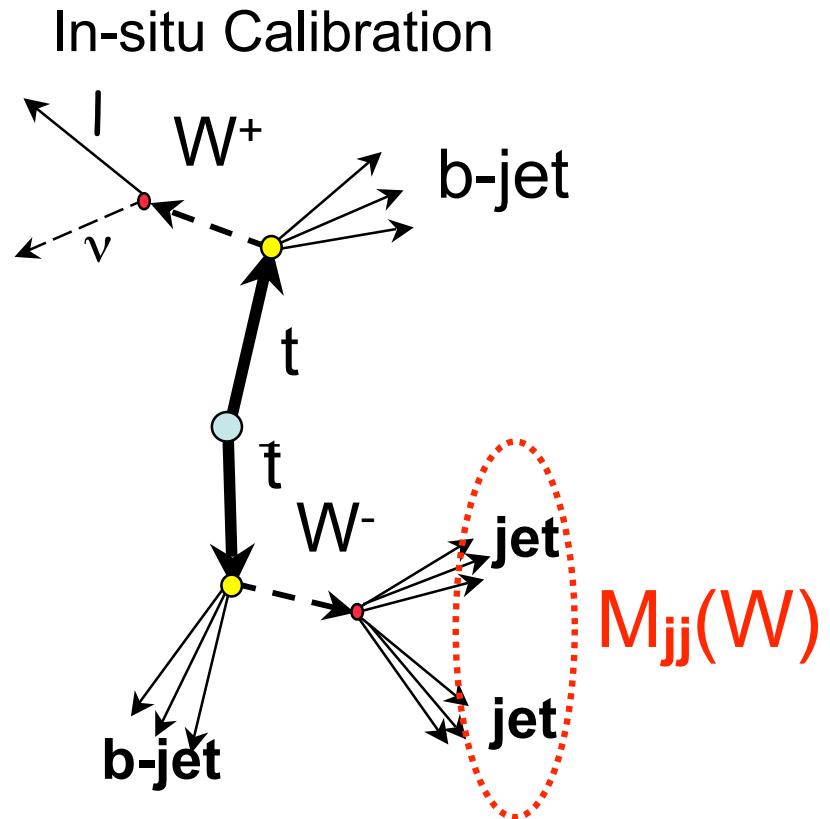
- Calculate probability as top mass for all combinations in each event by Matrix Element calculation
 - maximize dynamic info.
- Build likelihood directly from the probabilities.
- Calibrate measured mass and error using simulated events

Jet Energy Scale(JES) Uncertainties



About 3% of M_{top}

See R. Hirosky's talk



JES uncertainty:
mostly statistical,
scaled with lum

Strategy

- Precision
- Consistency (different channels, methods)
- New Physics (bias)

Method	Njets		B-tag		JES			Rec. variables
	Exact	+extra	Yes	No	Wjj+std	Wjj	No	
LJ	TMP	4						mt, mjj, Lxy
	ME							P(Mt,JES)
DIL	TMP	2						mt
	ME							P(Mt)
All-J	TMP+ME	6						mt, mtb



both



Only D0



Only CDF

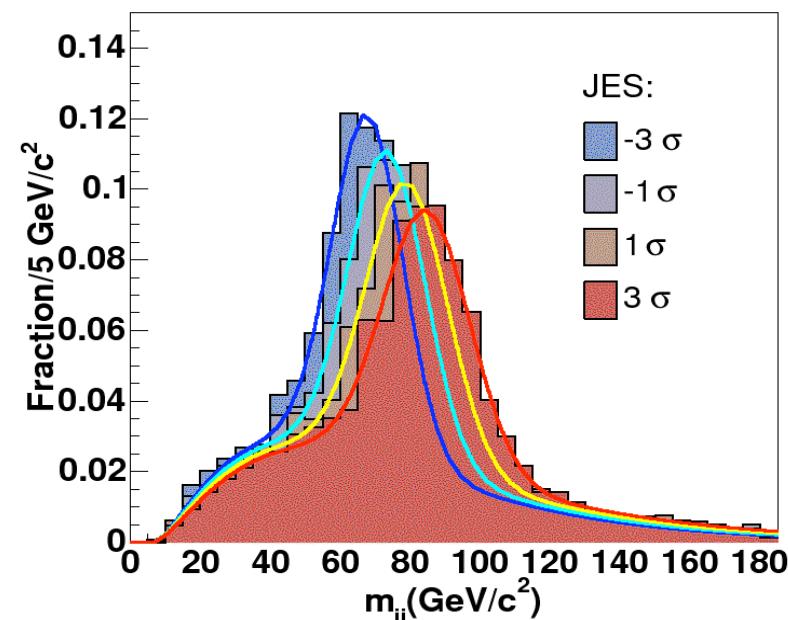
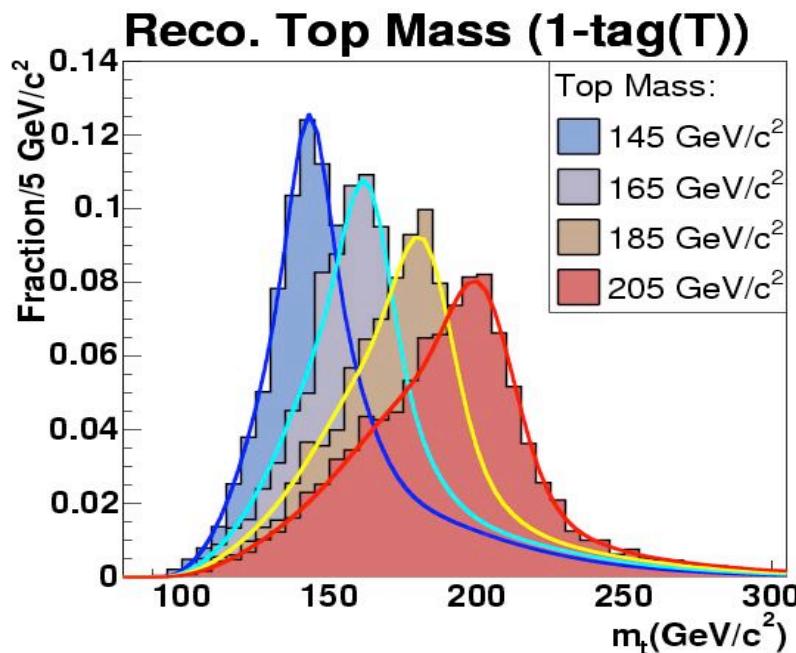
Template Method in lepton+jet

➤ χ^2 kinematic fitter

$$\chi^2 = \sum_{i=l,4 \text{ jets}} \frac{(\hat{p}_T^i - p_T^i)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(\hat{p}_T^{UE} - p_T^{UE})^2}{\sigma_j^2}$$

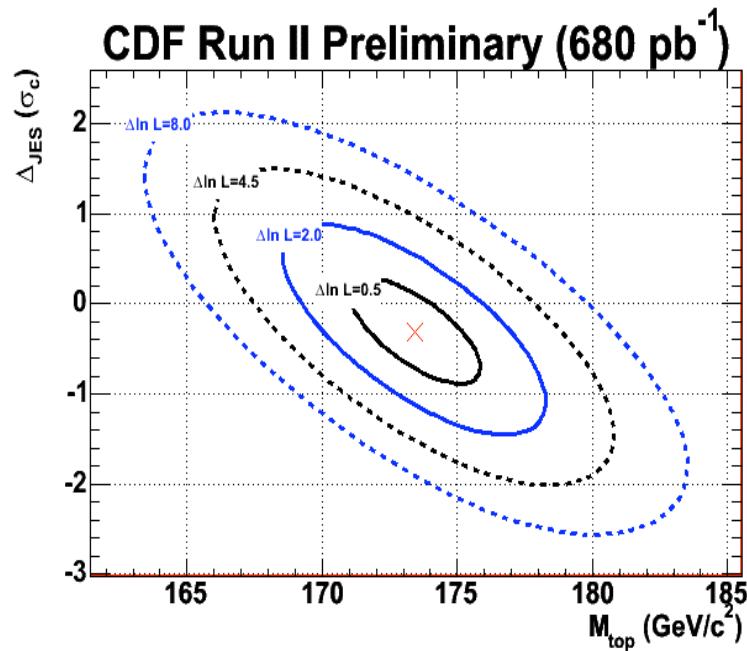
$$+ \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} + \frac{(m_{lv} - m_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - m_t)^2}{\Gamma_t^2} + \frac{(m_{blv} - m_t)^2}{\Gamma_t^2}$$

➤ Select reco. m_t from assignment yielding lowest χ^2



Mtop and JES : by likelihood fit using shape comparisons of m_t & m_{jj} dist.

Template Results in lepton+jets

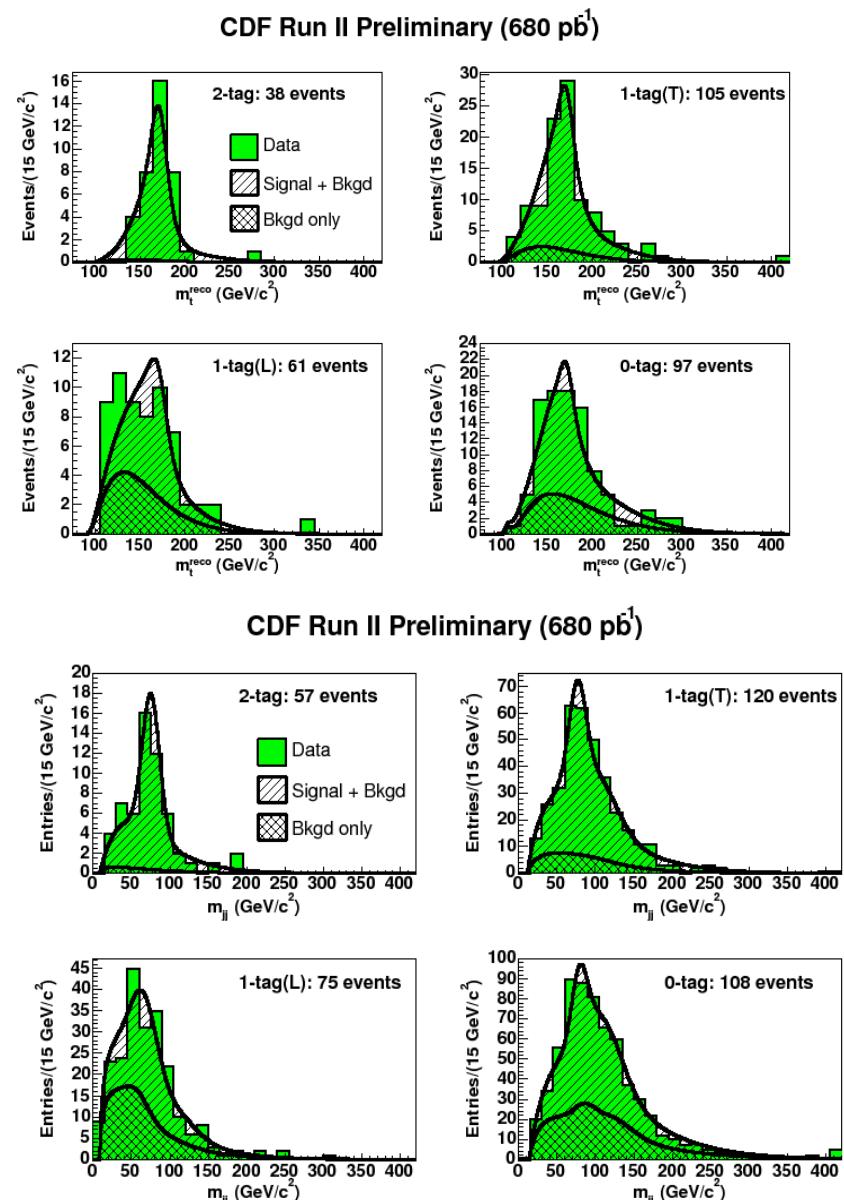


$M_{\text{top}} = 173.4 \pm 3.5(\text{stat.} + \text{JES})$
 $\pm 1.3 \text{ (syst.) GeV}/c^2$

World best single measurement!

40% improvement on JES
using in-situ JES calibration

Un-ki Yang, HCP 2006



Matrix Element Method in lepton+jets

- Maximize kinematic and dynamic information
- Calculate a probability per event to be signal or background as a function of the top mass
- Signal probability for a set of measured jets and lepton (x)

$$P(x; M_{\text{top}}, \text{JES}) = \frac{1}{\sigma} \int dq_1 dq_2 f(q_1) f(q_2) d\sigma(y; M_{\text{top}}) W(x, y, \text{JES})$$

Differential cross section:
LO ME ($q\bar{q} \rightarrow t\bar{t}$) only

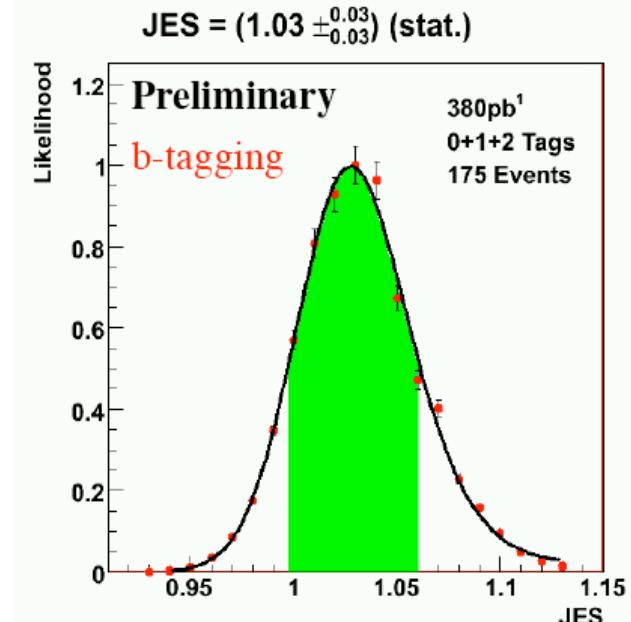
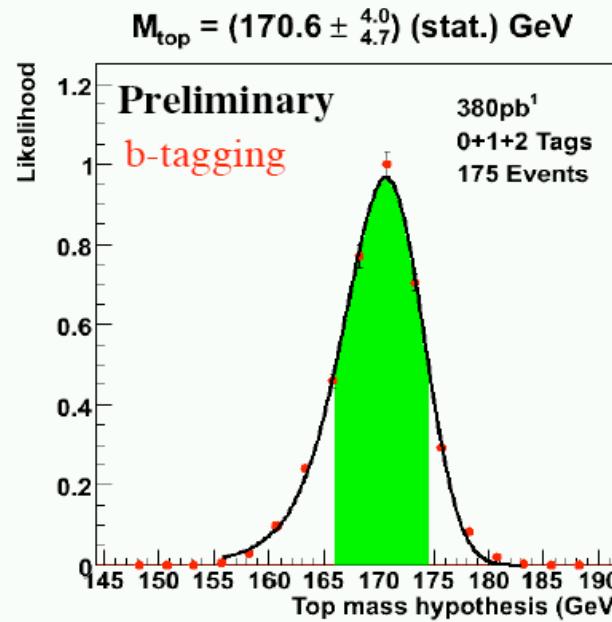
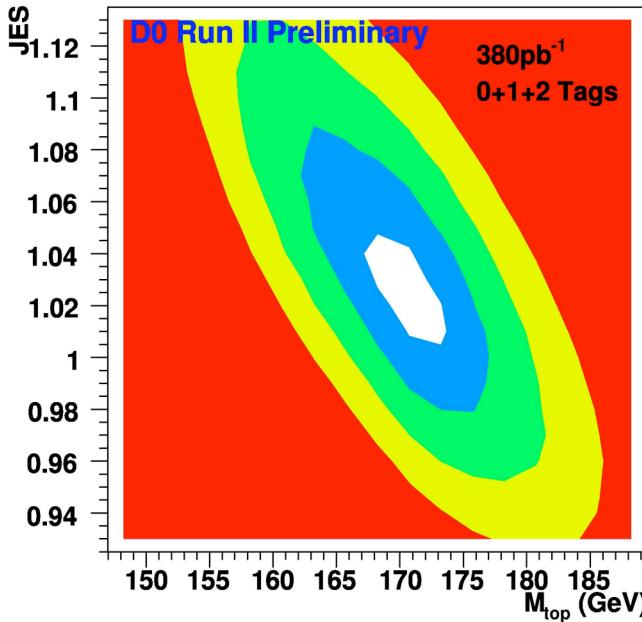
Transfer function: probability
to measure x when parton-level
 y was produced

- JES is a free parameter, constrained in situ by mass of the W
- Background probability is similar, but no dependence on M_{top}

$$L(f_{\text{top}}, M_{\text{top}}, \text{JES}) \propto \prod_i^{N_{\text{events}}} \left(f_{\text{top}} P_{\text{top},i}(M_{\text{top}}, \text{JES}) + (1 - f_{\text{top}}) P_{\text{bkgd},i}(\text{JES}) \right)$$



M.E. Results in lepton+jets



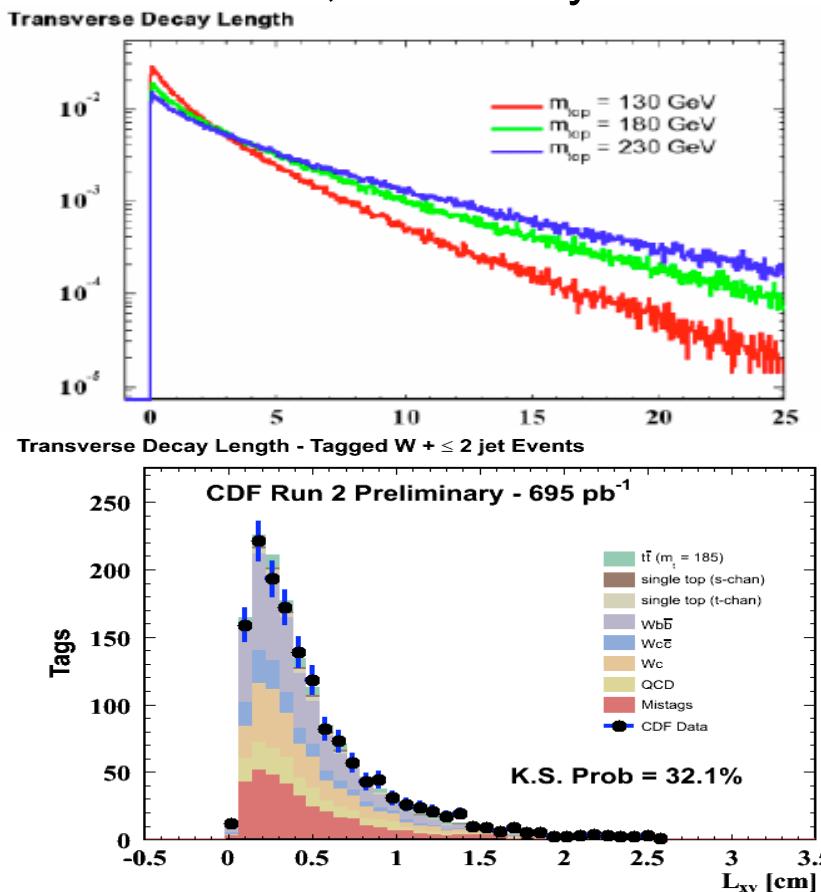
$$M_{\text{top}} = 170.6^{+4.0}_{-4.7} (\text{stat. + JES}) \pm 1.4 (\text{syst.}) \text{ GeV}/c^2$$

- Reduced the JES error with in-situ calibration, consistent with external calibration (JES=1)
- The b-tagging information improves $\delta M_{\text{top}}(\text{stat})$ by 35% (17% expected)

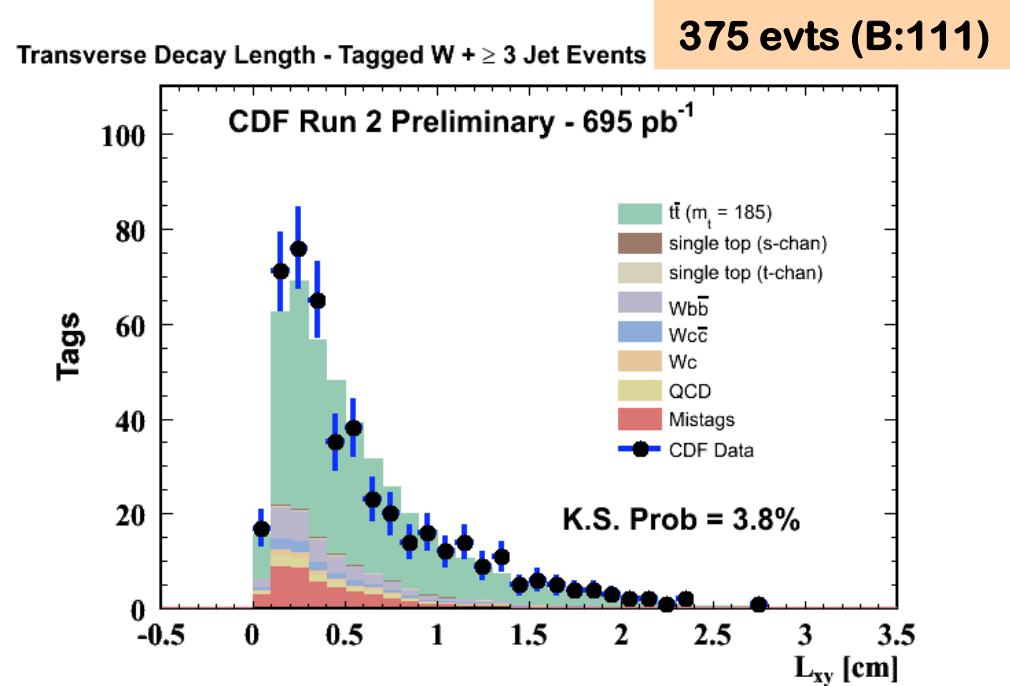
Template using Decay Length (Lxy)

- Uses the average transverse decay length, Lxy of the b-hadrons
- B hadron decay length \propto b-jet boost $\propto M_{top}$ ($>= 3$ jets)

PRD 71, 054029 by C. Hill et al.



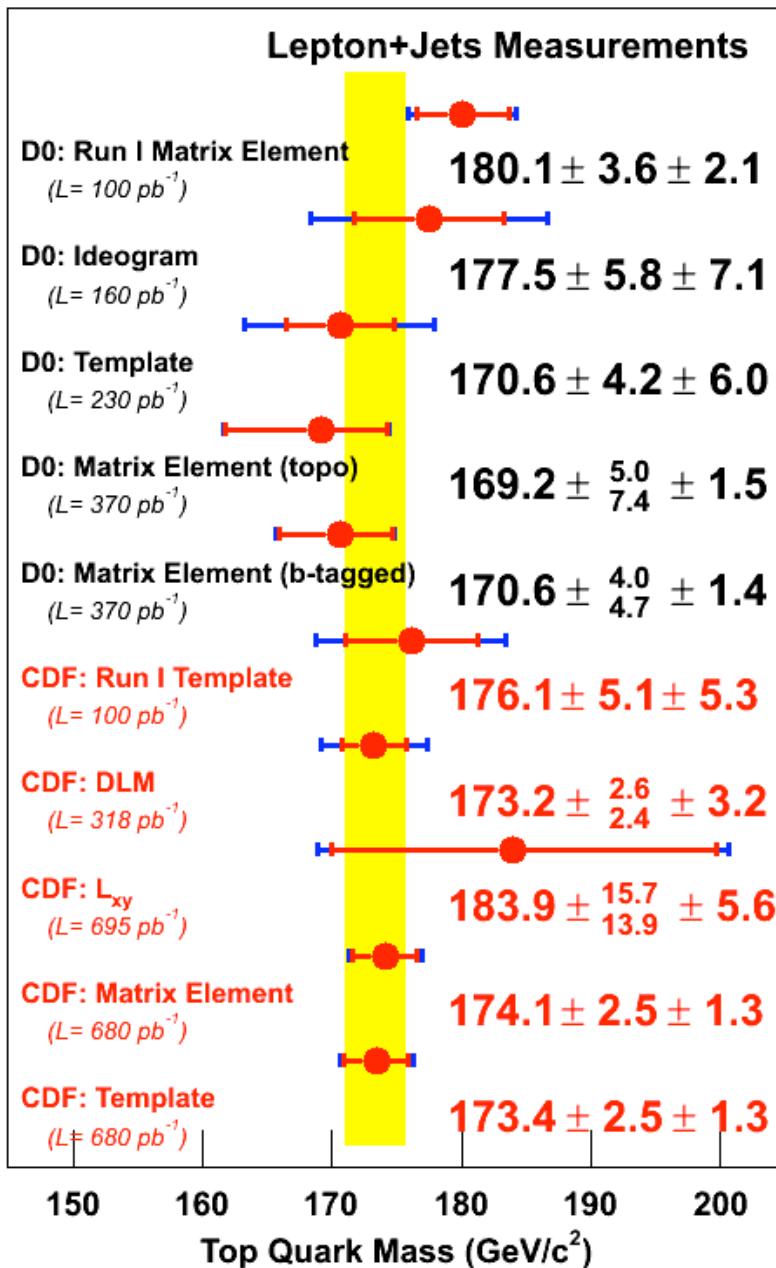
Insensitive to JES,
but need Lxy simulation



$$M_{top} = 183.9^{+15.7}_{-13.9} \text{ (stat)} \pm 0.3 \text{ (JES)} \pm 5.6 \text{ (syst)} \text{ GeV}/c^2$$

Statistics limited, but can make
big contributions at Run IIb, LHC

Summary in lepton+jets

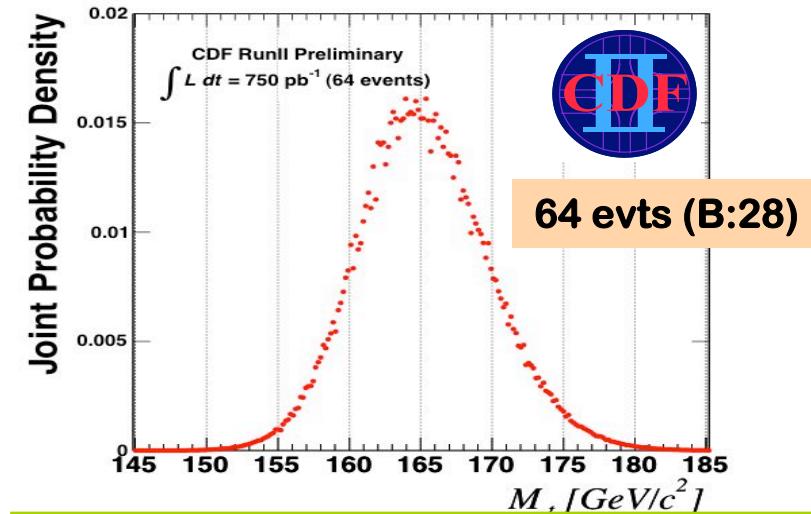
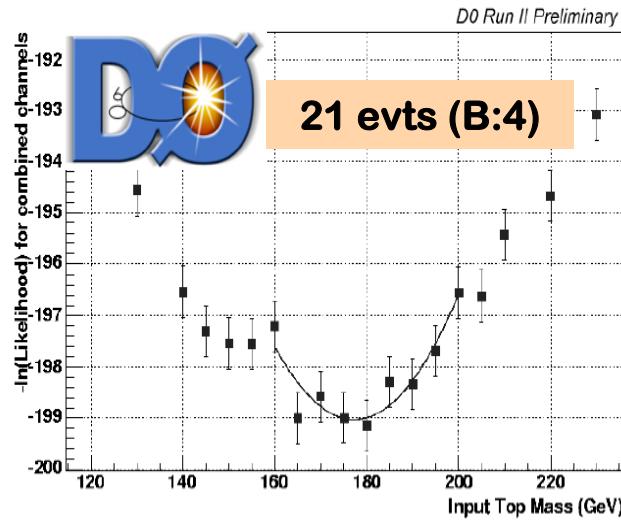


Systematic $\Delta M_{\text{top}}(\text{GeV}/c^2)$	TMT (CDF)	ME (D0)
JES	(1.8)	(3.4)
Residual JES	0.7	0.8
B-jet JES	0.6	0.7
ISR/FSR	0.5	0.5
Bkgd Shape	0.5	0.3
Generators	0.3	
PDFs	0.3	0.1
Method	0.3	0.5
B-tagging	0.1	0.2
TOTAL	1.3	1.4

All consistent!!

Methods in dilepton

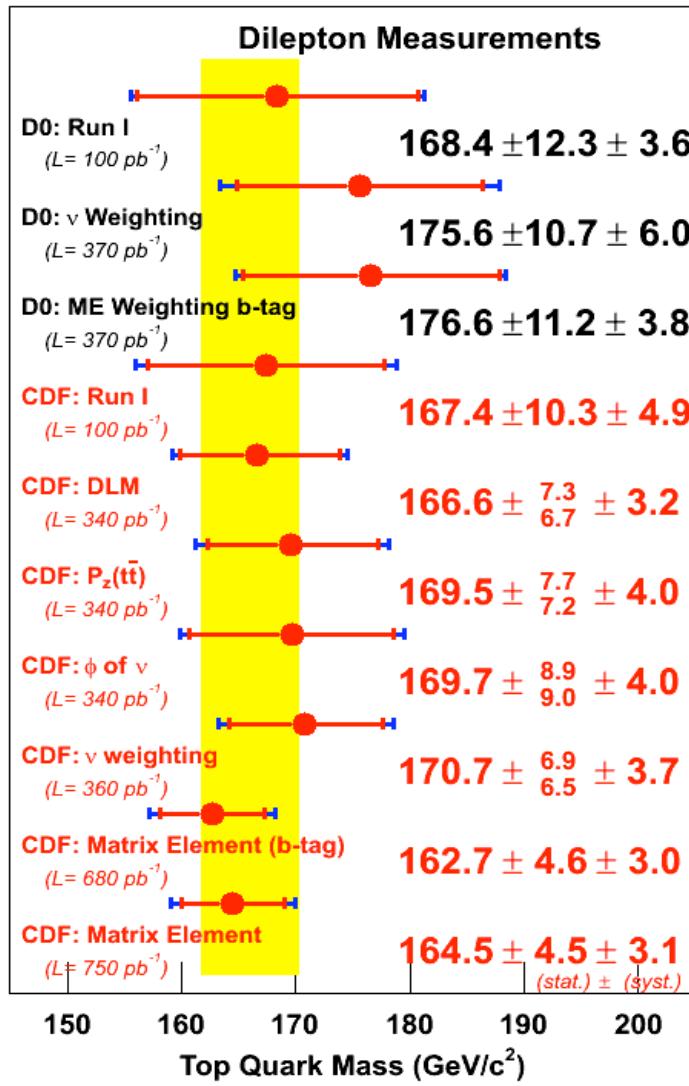
- Unconstrained system: 2 neutrinos, but 1 missing E_T observable
 - Template:
 - Assume $\eta(v)$ (or $\phi(v)$, $P_Z(t\bar{t})$)
 - Sum over all kinematic solutions, and (l,b) pairs, select the most probable value as a reco. m_t
 - Matrix Element:
 - Integrated over unknown variables using the LO M.E., assuming jet angles, lepton are perfect, and jets are b's
 - Obtain $P(M_{top})$ for signal and backgrounds
 - Calibrate off-set in pull and pull width using fully simulated MC



$$M_{top} = 175.6 \pm 10.6 \text{ (stat)} \pm 6.0 \text{ (syst)} \text{ GeV}/c^2$$

$$M_{top} = 164.5 \pm 4.5 \text{ (stat)} \pm 3.1 \text{ (syst)} \text{ GeV}/c^2$$

Summary in dileptons

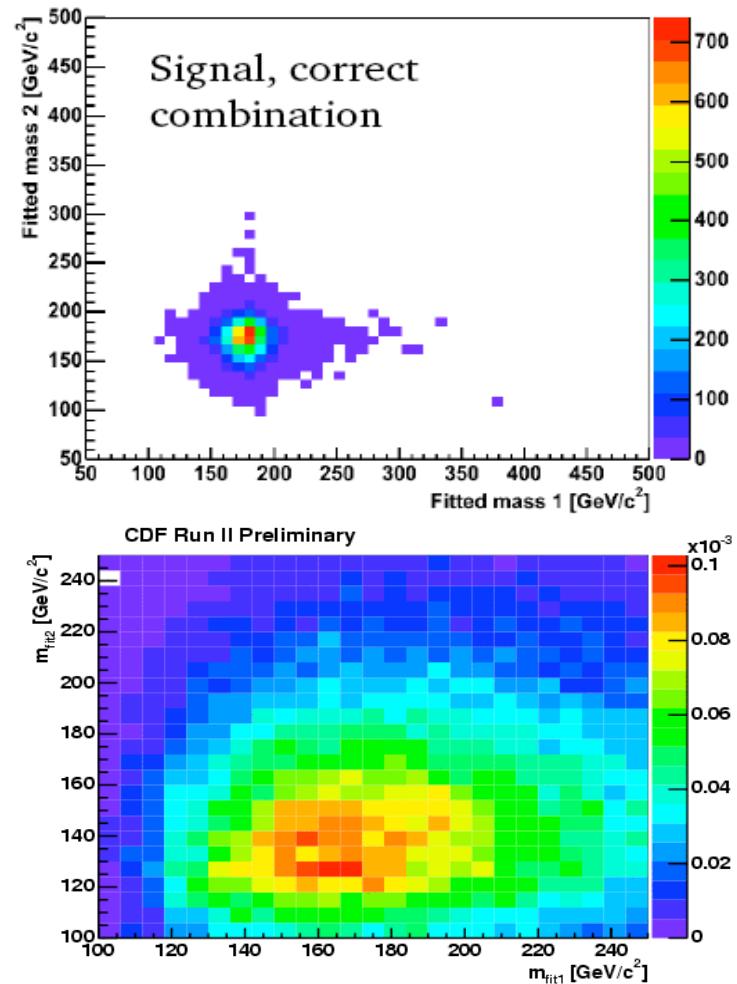


Systematic $\Delta M_{\text{top}} (\text{GeV}/c^2)$	ME (CDF)	TMT (D0)
JES	2.6	3.5
Bkgd Shape	0.8	0.2
Sample composition	0.7	
ISR/FSR	0.7	0.8
Generators	0.5	
PDFs	0.6	0.9
MC stats	0.8	0.3
Method	0.3	0.6
TOTAL	3.1	3.8

All consistent!!

All-Jets

- Largest BR, and no missing information, but large backgrounds, S/B = 1:
8 even after 1 b-tag
- Event Selection
 - $E_T / \sqrt{(\sum E_T)} < 3 \text{ (GeV)}^{1/2}$
 - $\sum E_T \geq 280 \text{ GeV}$
 - $n_{\text{b-tag}} \geq 1 \text{ (b-tag)}$
 - Exactly 6 jets
- χ^2 kinematic Fitter with W mass constraint: fit **two** top quark masses (m_1, m_2), then use χ^2 value to weight each permutation



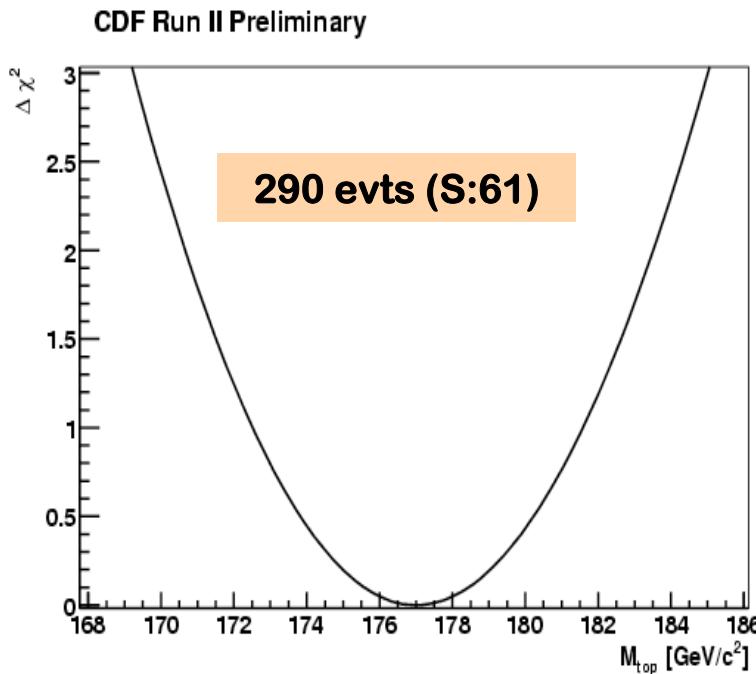
Ideogram in All-jets

- 2D likelihood:

$$\mathcal{L}(M_{top}, C_s) = \sum_{i=1}^{90} w_i [C_s Signal + (1 - C_s) Bkgd]$$

Convolution of Breit-Wigners and Gaussian resolution functions

$$\text{where } Signal(m_i^1, m_i^2, \sigma_1^2, \sigma_2^2, M_{top}) = p_{mat} S_{mat} + (1 - p_{mat}) S_{comb}$$



$$M_{top} = 177.1 \pm 4.9 (\text{stat}) \pm 4.3 (\text{JES}) \pm 1.9 (\text{syst}) \text{ GeV}/c^2$$

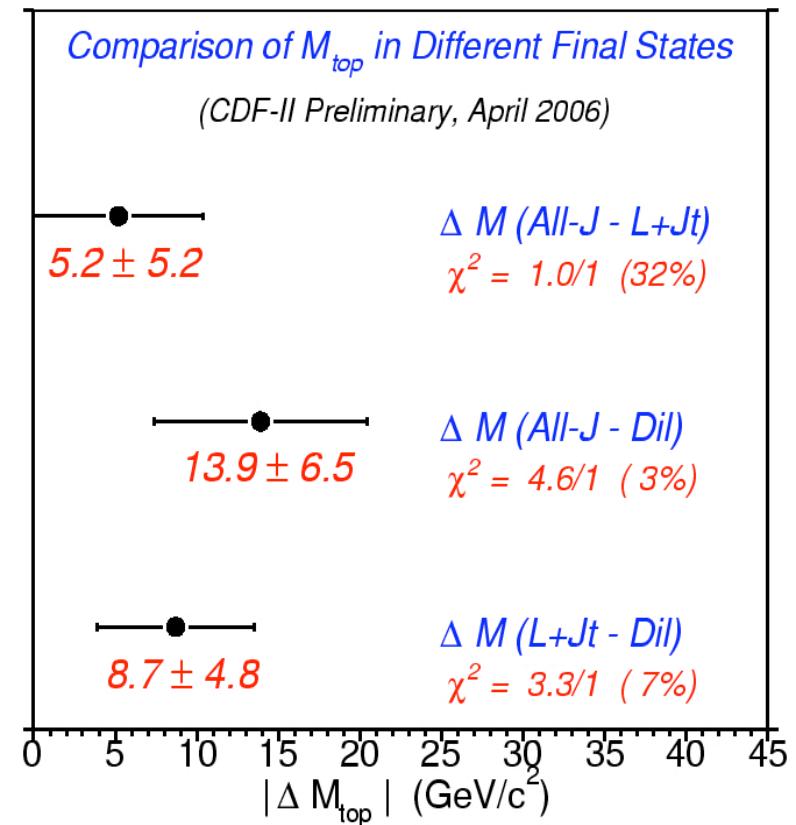
- First Tevatron Run II all jets M_{top} measurement
- Systematically limited M_{top} Results
- JES is correlated with S/B ratio

Combining M_{top} Results

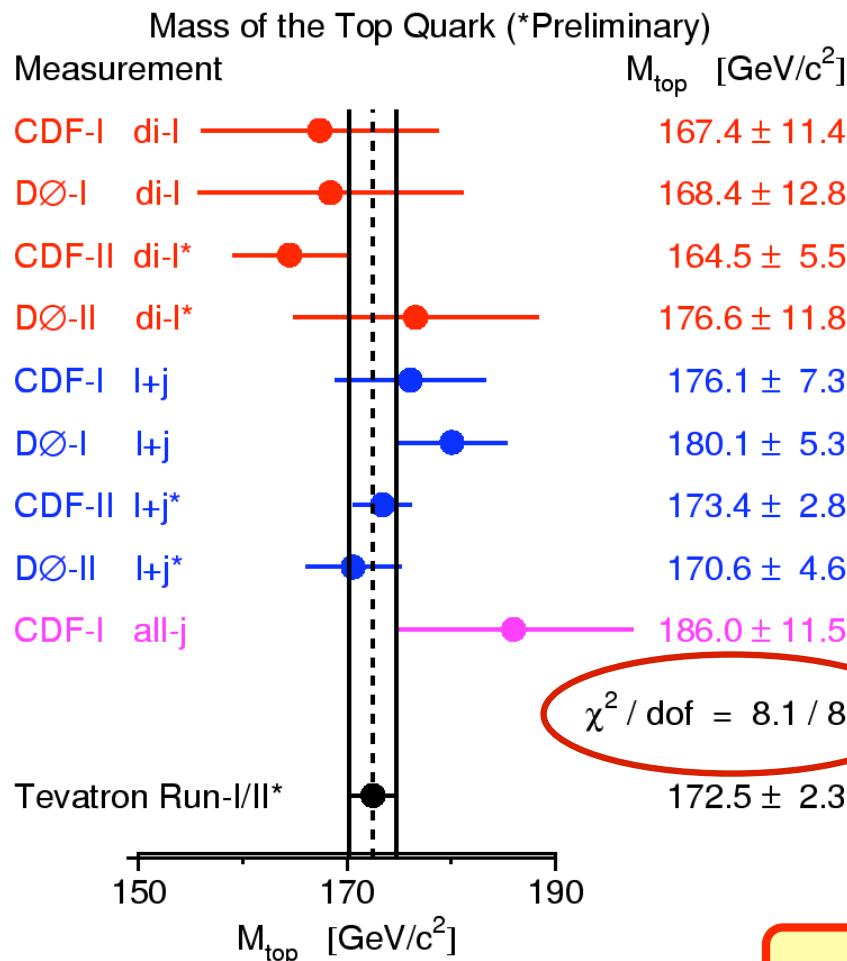
- Are the channels consistent ? (check by CDF)

$M_{top}(\text{All Jets}) = 178.7 \pm 5.5 \text{ GeV}/c^2$
 $M_{top}(\text{Dilepton}) = 164.8 \pm 4.8 \text{ GeV}/c^2$
 $M_{top}(\text{Lep+Jets}) = 173.5 \pm 2.8 \text{ GeV}/c^2$

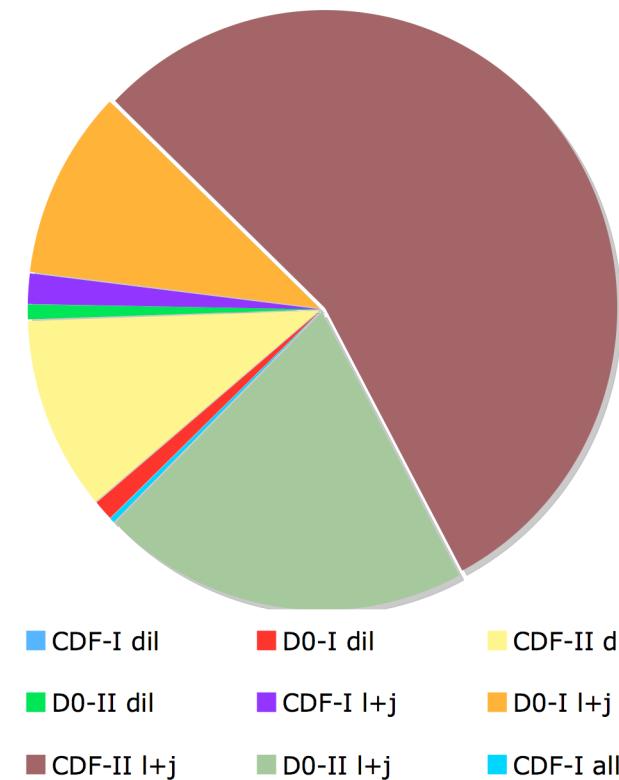
- Any systematic shift?
 - Missing systematic?
 - Bias due to new physics signal?



Tevatron Average



Weight (%)



$$M_{\text{top}} = 172.5 \pm 2.3 \text{ GeV}/c^2 (1.3\%)$$

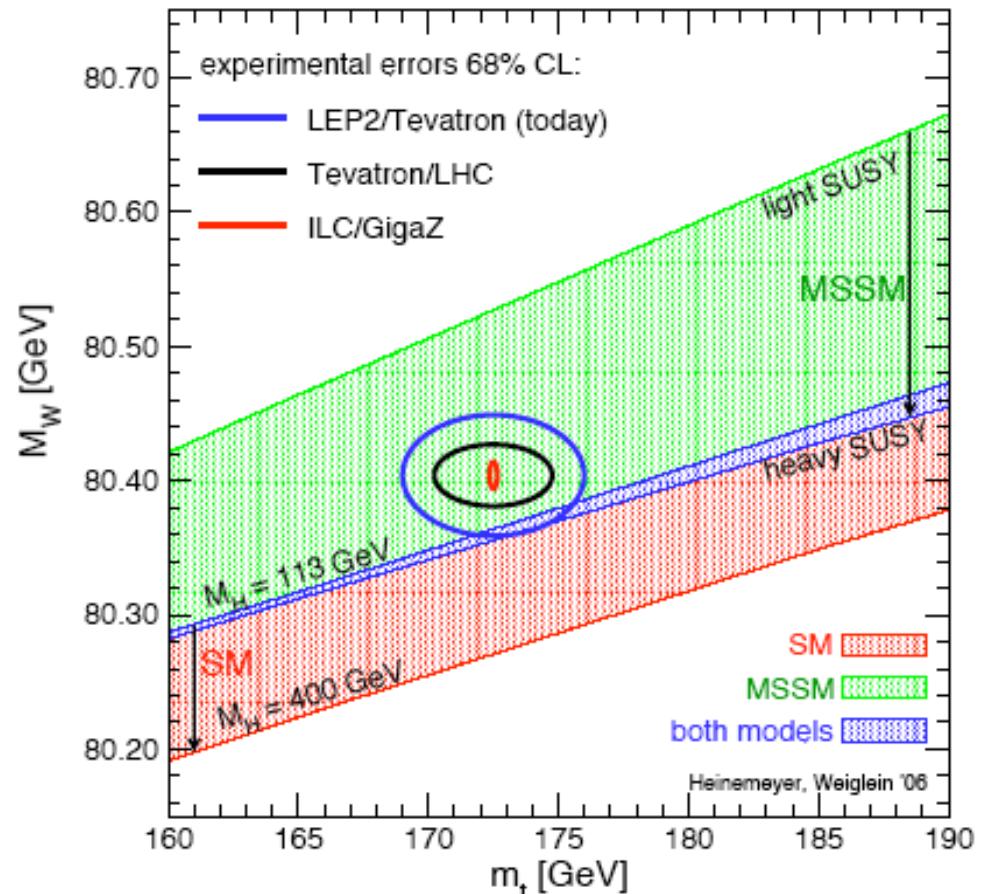
Implication for Higgs and SUSY

- A Precision EWK Fit

$$M_H = 89^{+42}_{-30} \text{ GeV}/c^2$$

$$M_H < 175 \text{ GeV}/c^2 @ 95\% CL.$$

- Direct search(LEP):
 $M_H > 114 \text{ GeV}$
- New result favors SUSY over SM, light SUSY



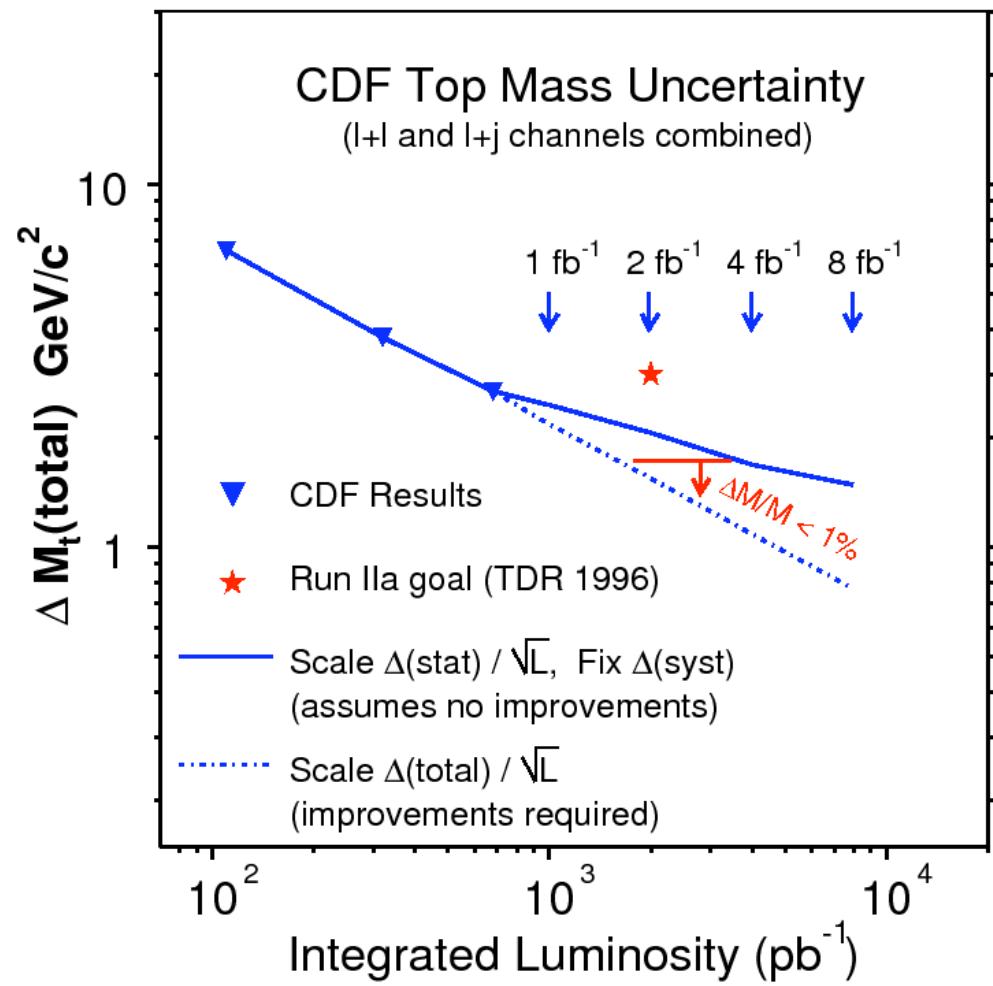
By Heinemeyer et al. (MSSM: $m_H < 140 \text{ GeV}$)

Few Lessons from Tevatron

- A major JES uncertainty is greatly reduced by the Wjj in-situ calibration (40% improvement with 700pb-1 data)
- B-jet specific uncertainty is small (<0.7 GeV)
 - Heavy-quark fragmentation
 - Color-interference
 - Semi-leptonic decay
- Good b-tagger is important
- Effect of the higher order (NLO) is small at the Tevatron (<0.5 GeV)
- qq vs gg events have different kinematics (2-2.5 GeV difference in top mass: CDF)
- Effect of the multiple interaction is small
- Effect of the backgrounds is small (except all-jets channel)

Summary and Future

- Achieved 1.3% precision of the M_{top} measurement (Run IIa goal, δM_{top} to $\sim 3 \text{ GeV}/c^2$ using only 30% data)
- Developed many tools (useful for LHC)
- With full Run-II dataset, able to achieve δM_{top} to $< 1.5 \text{ GeV}/c^2$
- More precision and consistency!!!



Syst. : ISR/FSR/NLO (backup)

- Method in hand to use Drell-Yan events to understand and constrain extra jets from ISR
 - Constraint scales with luminosity
 - Easily extendible to FSR.
- MC@NLO sample shows no add'l N LO uncertainty is needed.

